

Gold(I) Complexes of 1,2-bis(butylphenylphosphino)ethane and *cis*-1,2-bis(butylphenylphosphino)ethylene

David S. Khanye¹, Judy Caddy^{1,2*} and Marcus Layh¹

¹ School of Chemistry, University of the Witwatersrand, Private Bag 3, WITS, 2050, South Africa.

² Project AuTEK, Mintek, Private Bag X3015, Randburg, 2125, South Africa.

*To whom the correspondence should be addressed.
E-mail: judyc@mintek.co.za

Abstract

The well established and known chemistry of metal phosphides as nucleophilic and reactive precursors has been used as a suitable synthetic approach in the synthesis of 1,2-bis(butylphenylphosphino)ethane (bppe) (**5**) and *cis*-1,2-bis(butylphenylphosphino)ethylene (bppey) (**6**). Adducts of bridged and bis-chelated gold(I) with **5** and **6**, as well as silver(I) with **5**, have been prepared in moderate to good yields. These complexes have been characterised by solution NMR spectroscopy, mass spectrometry (FAB) and microanalysis in case of **10a**, **10b** and **11**.

Introduction

Tertiary bis-phosphines of the form $R_2P-(CH_2)_n-PR_2$ ($n = 1 - 4$ and $R = Me, Et, t-Bu$ and Ph) and *cis*- $R_2PCH=CHPR_2$ ($R = Ph$) are often used as chelating ligands for a wide range of transition metals.[1-4] These ligands have shown wider applications in metal complexation reactions and have attracted much attention, especially in the fields of medicine and catalysis.[5-9] They are versatile ligands in stabilising metal ions, especially transition metals in their lower oxidation states,[10] and have contributed to the fundamental understanding of the coordination chemistry of transition metals.[6] It is now well established that the strong π -acceptor ability of phosphines enables the stabilisation of even relatively electron-rich transition metals.[11]

Since the early application of 1,2-bis(diphenylphosphino)ethane (dppe) (**1**) and *cis*-1,2-bis(diphenylphosphino)ethylene (dppey) (**2**) (Figure 1) as chelating phosphine ligands, research efforts have more recently been centred on modifying the organic substituents on the phosphorus atom by the introduction of alkyl groups,[12] pyridyls,[13,14] or substituted aryls such as *o*-anisyl, 1-naphthyl, *c*- C_6H_5 ,[15] in an effort to tailor the ligand to suit the specific application. The modification of bis-phosphines has been extended to the introduction of solubilising groups into the ethane bridge of dppe.[16] Thus, properties such as the electronic nature, the steric requirements or solubility of the ligand and their corresponding metal complexes can be fine-tuned to suit the desired application.

Gold(I) has been known to form numerous complexes with phosphine ligands, the majority of them being two-coordinate gold complexes. It was not until 1984, that ^{31}P NMR studies of the bridged di-gold diphosphine complex, $[(AuCl)_2(dppe)]$ (**3**), in presence of free dppe ligand demonstrated the formation of a four-coordinate complex, $[Au(dppe)_2]^+Cl^-$ (**4**) (Figure 2).[17]

Silver, as the lighter congener of gold, shows an equally interesting coordination chemistry with phosphine ligands leading to a large variety of complexes of different nuclearity (mononuclear to polynuclear)[18] and bonding modes (bridging and chelating).[19]

Due to our ongoing research in the coordination chemistry of metal-phosphine complexes, we became interested in the coordination chemistry of ligands **5** and **6**. [20,21] Thus, the research efforts presented herein compliment reports which describe the significant change in metal complex properties as a result of substitution on the phosphorus atom or the bridging carbon atom of dppe analogues.[16] Here, we report the synthesis of **5** and **6** (Figure 3), as modified analogues of **1** and **2**, and their subsequent metal complexation with gold and silver (in case of **5**).

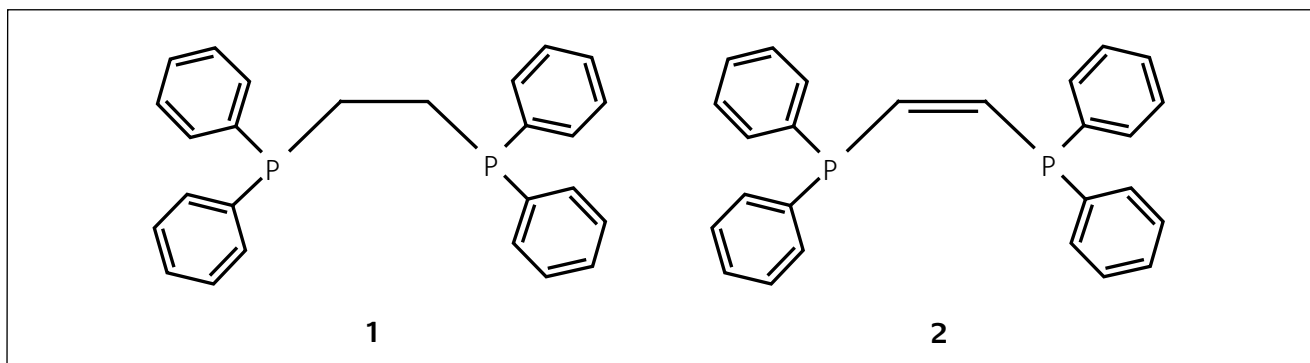


Figure 1

Bis-phosphine ligands, dppe and dppey.

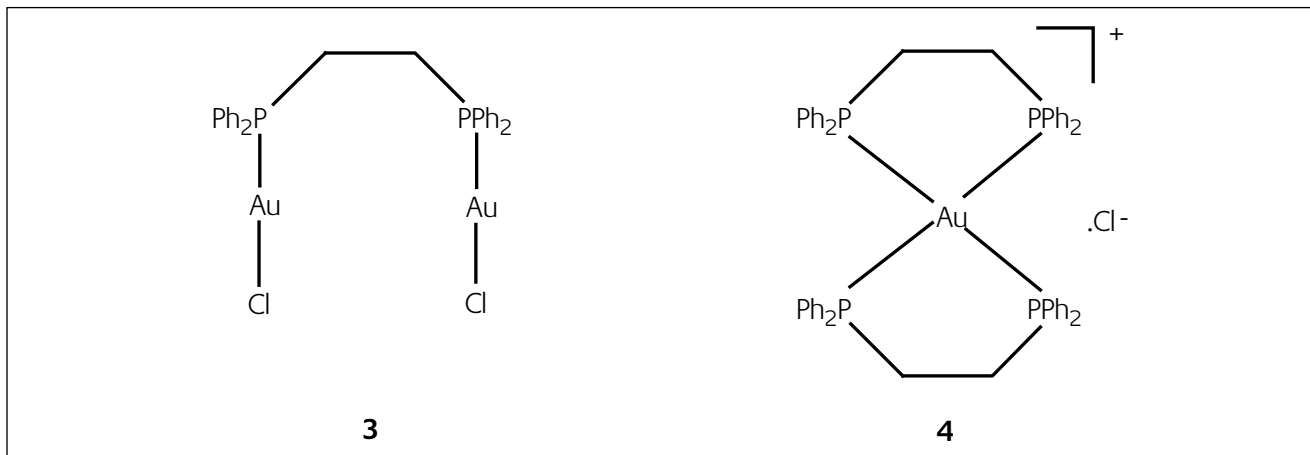


Figure 2

Bis-phosphine gold complexes, $[\text{AuCl}_2(\text{dppe})]$ and $[\text{Au}(\text{dppe})_2]^+\text{Cl}^-$.

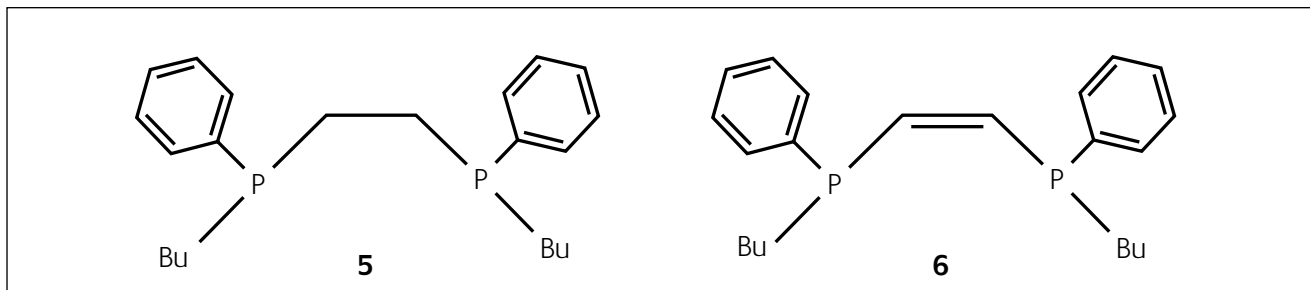


Figure 3

Modified bis-phosphine ligands with butyl groups, bppe and bppey.

Experimental Section

All manipulations were carried out under argon atmosphere, using standard Schlenk-techniques. Solvents were distilled from sodium/benzophenone ketyl or calcium hydride and degassed. Deuterated solvents were degassed by freeze-drying and kept under argon and on molecular sieves. NMR spectra were recorded in CDCl_3 or d_6 -DMSO at 298 K using the following Bruker instruments, AVANCE 300 (^1H 300.13; ^{31}P 121.5; ^{13}C 75.5 MHz) AVANCE DRX 400 (^1H 400.13; ^{31}P 161.9; ^{13}C 100.6 MHz) and referenced internally to residual solvent resonances (data in δ) in the case of ^1H and ^{13}C spectra, while the ^{31}P spectra were referenced externally to 85% H_3PO_4 . All NMR spectra other than ^1H NMR were proton-decoupled.

FAB-MS spectra were collected using a VG70-SEQ instrument in positive ion mode. Elemental analyses were determined on a Thermo Flash EA1112 CHNS-O elemental analyzer at the University of Cape Town. The following abbreviations are used throughout the experimental section: bs = broad singlet, d = doublet, dd = doublet of doublet, m = multiplet, s = singlet. Coupling constants, J , are measured in Hertz (Hz).

Synthesis of butyldiphenylphosphine, $\text{Ph}_2\text{P}^{\text{Bu}}$

Ph_3P (26.4 g, 104.8 mmol) was dissolved in 100 cm^3 of tetrahydrofuran (THF). The mixture was added dropwise at

0 °C to a suspension of granular lithium metal (1.60 g, 230.5 mmol) in 100 cm³ of THF. The reaction was stirred at 0 °C for 1 hr. This was accompanied by a colour change from colourless to red-brown. The mixture was allowed to warm to room temperature and then stirred for 72 hrs. The unreacted lithium metal was removed by filtration. To the red-brown filtrate, *n*-butylchloride (22.7 cm³, 217.4 mmol) in 20 cm³ hexane was added dropwise at 0 °C, while rapidly stirring. The reaction mixture was stirred at room temperature overnight. After removing the volatiles *in vacuo*, 100 cm³ of dried hexane were added to the red-brown viscous oil to precipitate LiCl from the solution. The colourless solution was filtered by means of a cannula to remove LiCl. Hexane was removed from the filtrate *in vacuo* to give a yellow viscous oil, which became a colourless liquid after distillation under vacuum. Yield: 13.97 g, 64%. Boiling point: 105 – 110 °C / 85.5 x 10⁻⁴ mmHg (lit. [22]. 100 – 102 °C / 2.63 x 10⁻⁴ mmHg). ³¹P-NMR (CDCl₃): δ -15.9 ppm (s).

Synthesis of Ph(Bu)PCH₂CH₂P(Bu)Ph (5)

Method A: A solution of Ph₂BuP (5 g, 20.6 mmol) in 25 cm³ THF was added dropwise to a suspension of granular lithium metal (0.285 g, 41.2 mmol) in 60 cm³ of THF at 0 °C. The reaction mixture was stirred at 0 °C for 1 hr. This was accompanied by a colour change from colourless to red-brown. The mixture was allowed to warm to room temperature and then stirred for 72 hrs. The unreacted lithium metal was removed by filtration. To the red-brown filtrate, 1,2-dichloroethane (1.02 g, 10.3 mmol) in 25 cm³ hexane was added dropwise at 0 °C, while rapidly stirring. The reaction mixture was stirred at room temperature overnight. The white-yellow reaction mixture was extracted with hexane. The hexane was removed *in vacuo* to give a yellow oil (0.5 g, 17%). **Method B:** 1,2-Bis(diphenylphosphino)ethane (dppe) (10.0 g, 25.1 mmol) was dissolved in 100 cm³ of THF. Further, the mixture was added dropwise to a suspension of granular lithium metal (0.784 g, 112.9 mmol) in 120 cm³ at 0 °C. The reaction was stirred at 0 °C for 1 hr. This was accompanied by a colour change from colourless to red-brown. The mixture was allowed to warm to room temperature and then stirred for 72 hrs. The unreacted lithium metal was removed by filtration. To the red-brown filtrate, *n*-butylchloride (12.3 cm³, 112.9 mmol) in 20 cm³ of hexane was added dropwise at -30 °C, while rapidly stirring. The reaction mixture was stirred at room temperature overnight. After removing the solvent *in vacuo*, a further 100 cm³ of hexane were added to the red-brown viscous oil to precipitate LiCl from the oil. The hexane was removed *in vacuo* to give a yellow viscous oil, that after vacuum distillation yielded a colourless oil. Yield: 4.85 g, 54 % (Mixture of diastereomers). Boiling point: 170 – 175 °C/140 mmHg. ¹H-NMR (CDCl₃): δ 0.79 [t, CH₃, 6H, ³J_{H-H} = 6.9 Hz], 1.27 [unresolved t, CH₂, 8H], 1.56 – 1.61 [m, CH₂, 8H], 7.34 – 7.37 [m, 2Ph, 10H]. ³¹P-NMR (CDCl₃): δ

-19.6, -19.9. ¹³C-NMR (CDCl₃): δ 13.7 [s, CH₃], 24.1 – 24.3 [pseudo triplet, CH₂], 27.2 – 28.0 [m, CH₂], 128.2 [m, *p*-Ph], 128.6 [d, *o*/*m*-Ph, *J* = 3.3 Hz], 132.1 – 132.4 [m, *o*/*m*-Ph], 137.9 – 138.0 [m, *ipso*-Ph]. Mass spectrum (EI): *m/z* = 358.2 (10 %) [M]⁺, 301.3 (18 %) [M-Bu]⁺.

Synthesis of *cis*-Ph(Bu)PCH=CHP(Bu)Ph (6)

Ph₂PCH=CHPPh₂ (3.0 g, 7.57 mmol) was dissolved in 100 cm³ of THF. Further, the mixture was added dropwise to a suspension of granular lithium metal (0.236 g, 34.0 mmol) in 100 cm³ of THF at 0 °C. The reaction mixture was stirred at 0 °C for 1 hr. This was accompanied by a colour change from colourless to red-brown. The mixture was allowed to warm to room temperature and then stirred for 24 hrs. The unreacted lithium metal was removed by filtration. To the red-brown filtrate, *n*-butylchloride (4 cm³, 34.1 mmol) in 30 cm³ hexane was added dropwise at 0 °C, while rapidly stirring. The reaction mixture was stirred at room temperature overnight. The solvent was removed *in vacuo* to give a red-brown oil. Dry hexane (2 x 100 cm³) was added and a yellow-white precipitate formed, which was separated by filtration. The solvent was removed *in vacuo* off the filtrate and the obtained viscous oil was vacuum distilled to give a yellow oil. Yield: 2.09 g, 78 %. Boiling Point: 110 – 115 °C / 131.6 mmHg. ¹H NMR (DMSO): δ 0.86 [t, CH₃, 3H, ³J_{H-H} = 6.8 Hz], 1.28 – 1.40 [m, CH₂, 4H], 2.06 [pseudo t, CH₂, 2H, *J* = 7.2 Hz], 7.30 – 7.40 [m, Ph, CH=CH, 6H]. ³¹P NMR (DMSO): δ -16.7 ppm. ¹³C NMR (DMSO): δ 13.5 [s, CH₃], 23.4 [d, CH₂, *J*_{C-P} = 13.1 Hz], 26.4 [d, CH₂, *J*_{C-P} = 11.1 Hz], 27.6 [d, CH₂, *J*_{C-P} = 15.8 Hz], 128.3 [s, *p*-Ph], 128.4 [s, *m*/*o*-Ph], 132.1 [s, *o*/*m*-Ph], 132.3 [s, CH=CH], 138.5 [d, *ipso*-Ph, ¹J_{C-P} = 14.1 Hz]. Mass spectrum (EI): *m/z* = 356.2 (10 %) [M]⁺, 243.2 (100 %) [M-2Bu]⁺.

Synthesis of [(AuCl)₂Ph(Bu)PCH₂CH₂P(Bu)Ph] (8a)

[AuCl(SMe₂)] (0.17 g, 0.56 mmol) was dissolved in 10 cm³ of CH₂Cl₂. Further, a solution of Ph(Bu)PCH₂CH₂P(Bu)Ph (0.10 g, 0.28 mmol) in 5 cm³ of CH₂Cl₂ was slowly added to the reaction mixture at room temperature. After the mixture was stirred for 2 hrs at room temperature, the colourless solution was filtered by means of a cannula and the solvent removed *in vacuo* to give a white solid. Yield: 0.17 g, 74 %. ¹H NMR (CDCl₃): δ 0.81 – 0.92 [m, 2CH₃, 6H], 1.35 – 1.42 [m, CH₂, 8H], 2.07 – 2.10 [m, CH₂, 4H], 2.40 – 2.44 [m, CH₂, 2H], 7.46 – 7.63 [m, Ph, 10H]. ³¹P-NMR (CDCl₃): δ 33.2, 32.4. Mass spectrum (FAB): *m/z* = 786.7 (100 %) [M⁺-Cl], 555.4 (18 %) [Au(bppe)]⁺.

Synthesis of [(AuCl)₂Ph(Bu)PHC=CHP(Bu)Ph] (9)

[AuCl(SMe₂)] (0.17 g, 0.56 mmol) was dissolved in 10 cm³ of CH₂Cl₂. Further, a solution of Ph(Bu)PCH=CHP(Bu)Ph (0.10 g, 0.28 mmol) in 5 cm³ of CH₂Cl₂ was slowly added to the reaction mixture at room temperature. After the mixture was stirred for 3 hrs at room temperature, the brown solution was filtered by means of a cannula and the solvent removed *in vacuo* to give a brown solid. Yield: 0.18 g, 78 %. ¹H NMR (DMSO): δ 0.69 [t, CH₃, 3H, ³J_{HH} = 6.7 Hz], 1.24 [s, CH₂, 4H], 2.44 [m, CH₂, 2H], 7.40 – 7.60 [m, Ph / HC=CH, 6H]. ³¹P-NMR (DMSO): δ 31.5. Mass spectrum (FAB): *m/z* = 785.2 (0.5 %) [M⁺-Cl], 439.2 (25 %) [Au(PhPCH=CHPPh)]⁺.

Synthesis of [Au(Ph(Bu)PCH₂CH₂P(Bu)Ph)₂]Cl (10a)

[AuCl(SMe₂)] (0.49 g, 1.68 mmol) was dissolved in 10 cm³ of CH₂Cl₂. Further, a solution of Ph(Bu)PCH₂CH₂P(Bu)Ph (1.20 g, 3.35 mmol) in 10 cm³ of CH₂Cl₂ was added dropwise to the reaction mixture at room temperature. The reaction mixture was stirred overnight at room temperature. The colourless solution was filtered by means of a cannula and the solvent removed *in vacuo* to give a white solid. Yield: 1.35 g, 85 %. Calc. for C₄₄H₆₄AuP₂Cl: C, 55.7; H, 6.79 %. Found: C, 53.7; H, 6.77 %. ¹H NMR (CDCl₃): δ 0.70 – 0.86 [m, CH₃, 12H], 0.91 – 1.45 [m, CH₂, 16H], 1.91 – 2.15 [m, CH₂, 16H], 7.27 – 7.65 [m, Ph, 20H]. ³¹P-NMR (CDCl₃): δ 15.1 and 15.5 (Isomeric mixture). ¹³C-NMR (CDCl₃): δ 13.3 [s, CH₃], 23.6 [s, CH₂], 24.0 [s, CH₂], 27.4 [m, CH₂], 29.0 [m, CH₂], 128.8 [d, Ph, J_{C-P} = 9.8 Hz], 129.1 [br s, Ph], 130.4 [s, Ph], 133.0 [d, *ipso*-Ph, ¹J_{C-P} = 13.9 Hz]. Mass spectrum (FAB): *m/z* = 913.2 (100 %) [M⁺-Cl], 555.2 (22 %) [Au(bppe)]⁺.

Synthesis of [Au(Ph(Bu)PHC=CHP(Bu)Ph)₂]Cl (11)

[AuCl(SMe₂)] (0.44 g, 1.49 mmol) was dissolved in 15 cm³ of CH₂Cl₂. Further, a solution of Ph(Bu)PHC=CHP(Bu)Ph (1.09 g, 2.97 mmol) in 20 cm³ of CH₂Cl₂ was added dropwise to the reaction mixture at room temperature. The reaction mixture was stirred overnight at room temperature. The brown solution was filtered by means of a cannula and the solvent removed *in vacuo* to give a brown solid. The solid was washed with a mixture of CH₂Cl₂/hexane and then dried *in vacuo*. Yield: 1.31 g, 93 %. Calc. for C₄₄H₆₀AuP₂Cl: C, 55.9; H, 6.4 %. Found: C, 53.2; H, 5.97 %. ¹H NMR (DMSO): δ 0.73 [m, CH₃, 12H], 1.28 [m, CH₂, 18H], 2.36 [m, CH₂, 6H], 7.40 – 7.51 [m, Ph, CH=CH, 24H]. ³¹P-NMR (DMSO): δ 22.3. ¹³C-NMR (DMSO): δ 13.7 [s, CH₃], 20.4 [s, CH₂], 24.5 [m, CH₂], 28.0 [m, CH₂], 129.3 [s, *p*-Ph], 131.9 [m, *o/m*-Ph], 132.3 [m, *o/m*-Ph], 133.9 [s, -CH=CH-], 135.5 [m, *ipso*-Ph]. Mass spectrum (FAB): *m/z* = 909.3 (1.5 %) [M⁺-Cl], 795.2 (6.0 %) [M⁺-2Bu], 681.3 (100 %) [M⁺-4Bu].

Synthesis of [(AgNO₃)₂(Ph(Bu)PCH₂CH₂P(Bu)Ph)] (8b)

AgNO₃ (0.096 g, 0.57 mmol) was suspended in 15 cm³ of CH₂Cl₂. Further, a solution of Ph(Bu)PCH₂CH₂P(Bu)Ph (0.10 g, 0.28 mmol) in 10 cm³ of CH₂Cl₂ was slowly added to the reaction mixture at room temperature. After the mixture was stirred for 90 mins at room temperature, the colourised solution was filtered by means of a cannula and the solvent removed to give a brown solid. Yield: 0.1 g, 51 %. ¹H NMR (CDCl₃): δ 0.71 – 0.87 [m, CH₃, 6H], 1.22 – 1.29 [m, CH₂, 8H], 1.87 – 2.24 [m, CH₂, 8H], 7.31 – 7.60 [m, Ph, 10H]. ³¹P-NMR (CDCl₃): δ 9.5. [d, J_{Ag-P} = 225 Hz] ¹³C-NMR (CDCl₃): δ 13.50 [s, CH₃], 13.52 [s, CH₃], 23.8 [s, CH₂], 24.0 [s, CH₂], 27.7 [s, CH₂], 125.5 – 133.5 (m, Ph). Mass spectrum (FAB): *m/z* = 636.2 (6.8 %) [Ag₂(bppe)NO₃]⁺, 466.3 (61 %) [Ag(bppe)]⁺.

Synthesis of [Ag(Ph(Bu)P(CH₂CH₂P(Bu)Ph)₂)]ClO₄ (10b)

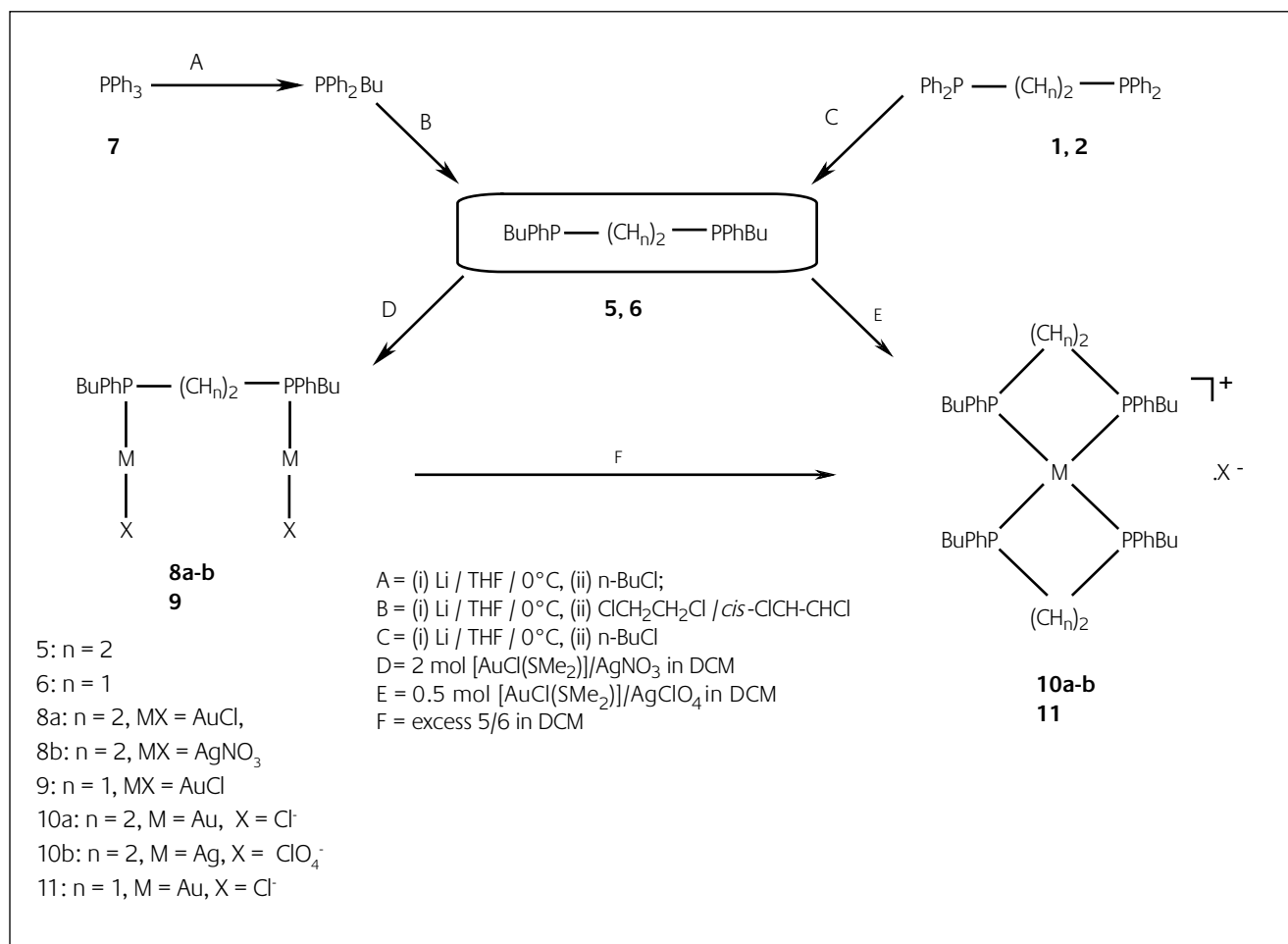
AgClO₄ (0.36 g, 1.68 mmol) was suspended in 10 cm³ of CH₂Cl₂. Further, a solution of Ph(Bu)PCH₂CH₂P(Bu)Ph (1.20 g, 3.35 mmol) in 10 cm³ of CH₂Cl₂ was added dropwise to the reaction mixture at room temperature. The reaction mixture was stirred overnight at room temperature. The colourless solution was filtered by means of a cannula and the solvent removed *in vacuo* to give a white solid. Yield: 1.40 g, 91 %. Calc. for C₄₄H₆₄AgClO₄: C, 57.2; H, 7.0 %. Found: C, 55.8; H, 6.82 %. ¹H NMR (CDCl₃): δ 0.72 – 0.88 [m, CH₃, 3H], 1.29–1.4 [m, CH₂, 4H], 1.9 – 2.3 [m, CH₂, 4H], 7.34 – 7.50 [m, Ph, 5H]. ³¹P-NMR (CDCl₃): δ -2.1 [d, J_{Ag-P} = 240 Hz]. ¹³C-NMR (CDCl₃): δ 13.6 [s, CH₃], 24.1 [s, br, CH₂], 27.8 [s, br, CH₂], 128.9 – 132.7 (Ph). Mass spectrum (FAB): *m/z* = 823.5 (31 %) [M⁺-ClO₄], 465.2(100 %) [Ag(bppe)]⁺.

Results and Discussion

Various synthetic routes exist for the preparation of bis-phosphine ligands. These include reaction methods such as reductive metallation of halophosphines, metal-halogen exchange, the metallation of primary and secondary phosphines with a strong base such as *n*-BuLi and the cleavage of P-C bonds in tertiary phosphines with an alkali metal.[17] In this work the latter principle of P-C bond cleavage, [23-27], has been employed towards the synthesis of novel bppe (**5**) and bppey (**6**).

The reaction schemes towards the synthesis of the ligands and metal complexes are summarised in Scheme 1. The first method involved the synthesis of *n*-butyldiphenylphosphine from triphenylphosphine (PPh₃) (**7**), and thereafter the desired ligand via a lithium butylphenylphosphide intermediate. The second method involved the synthesis of bppe directly from bis-phosphine, dppe (**1**) (Figure 1).

The synthesis of the bis-phosphine, bppe (**5**), via P-C bond



Scheme 1

Synthesis of cationic and neutral bis-phosphine group 11 metal complexes.

cleavage with an alkali metal involved the cleavage of PPh_3 (**7**) by lithium metal in tetrahydrofuran, which results in a source of lithium diphenylphosphide (LiPPh_2), a useful precursor for the preparation of bis-phosphine ligands. The reaction of PPh_3 and lithium metal (step A) *via* lithium diphenylphosphide intermediate was accompanied by a red-brown colour, characteristic of the formation of the metal-phosphide.[27] Treatment of the red-brown solution with a solution of *n*-butylchloride readily afforded the butyldiphenylphosphine precursor (Ph_2Pbu) in moderate yield (64%).

When Ph_2Pbu was subjected to similar reaction conditions the corresponding lithium butylphenylphosphide (LiPbuPh) intermediate (step B) was readily formed. In situ preparation of **5** by treating the LiPbuPh intermediate with 1,2-dichloroethane (step B) at low temperature yielded **5** in low yield (17 – 40%). Although, the stereospecific reaction of LiPPh_2 with either *cis*-1,2-dichloroethylene or *trans*-1,2-dichloroethylene to successfully yield the corresponding phosphines, *cis*- $\text{Ph}_2\text{PCH=CHPPh}_2$ or *trans*- $\text{Ph}_2\text{PCH=CHPPh}_2$ has been reported previously,[28] treating LiPbuPh with *cis*-1,2-dichloroethylene (step B) to form **6** resulted in a mixture of unidentifiable products.

Although many bis-phosphine ligands are being synthesised from PPh_3 , an attractive alternative approach, consisting of fewer synthetic steps, is the cleavage of the P-C

bonds of the $\text{Ph}_2\text{P}(\text{CH}_2)_x\text{PPh}_2$ ligands, where $n = 2$, $x = 2$ (**1**) or $n = 1$, $x = 2$ (**2**), by an alkali metal.[2,12,24-27] The reaction of $\text{Ph}_2\text{P}(\text{CH}_2)_x\text{PPh}_2$ (**1** or **2**) with at least 4mol equivalents of lithium metal to 1mol phosphine resulted in the formation of the characteristic red-brown lithium diphosphide intermediate, $\text{Li}(\text{Ph})\text{P}(\text{CH}_2)_x\text{P}(\text{Ph})\text{Li}$ (step C). Further reaction of $\text{Li}(\text{Ph})\text{P}(\text{CH}_2)_x\text{P}(\text{Ph})\text{Li}$ with 4.5 equivalents of *n*-butylchloride (step C) resulted in the formation of both ligands, **5** as mixture of isomers in moderate (54%) and **6** in good yield (78%). Both were characterised by both NMR spectroscopy and mass spectrometry.

The bis-phosphines **5** and **6** on complexation to gold(I), yielded the two and four co-ordinated gold(I) complexes **8a**, **9** and **10a**, **11** (Scheme 1). The bridged digold(I) complexes, **8a** and **9**, were synthesised by a procedure similar to the one described in the literature for $[(\text{AuCl})_2\text{dppe}]$, [1] which involved the addition of half an equivalent of the appropriate ligand, **5** or **6** (step D), to a solution of $[\text{AuCl}(\text{SMe}_2)]$ at room temperature, resulting in the formation of **8a** (57%) and **9** (78%) as white and light brown solids, respectively. The four co-ordinated bis-chelated complexes **10a** and **11** were synthesised *via* the established procedure of a 2:1 mol ratio of (P-P):Au(I).[1, 16,17,29] Thus, the reaction of two equivalents of **5** or **6** with a solution of $[\text{AuCl}(\text{SMe}_2)]$ in DCM (step E), readily afforded complexes **10a** and **11** in good yields (85%

Table 1: $^{31}\text{P}\{^1\text{H}\}$ chemical shift resonances of the bridged and bis-chelated gold(I) and silver(I) complexes.

^{31}P NMR					
Ligand Type	P-P	$[(\text{MX})_2(\text{P-P})]$	$[(\text{M}(\text{P-P})_2)\text{X}]$	Solvent	Metal
bppe*	-19.6; -19.9	32.4, 33.2	15.1, 15.5	CDCl_3	Au
		9.5	-2.1	CDCl_3	Ag
dppe	-11.9	31.5	20.8	CDCl_3	Au
		3.3	4.4	CDCl_3	Ag
bppey*	-16.7	31.5	22.3	DMSO	Au
dppey	-23.5	12.5	22.4	CDCl_3	Au

*This work

and 93%, respectively).

The complexation of **5** with stoichiometric amounts of silver salts $[\text{AgNO}_3]$ (step D) and $[\text{AgClO}_4]$ (step E), via a similar procedure described for the gold complexes, yielded both the bridged di-silver (**8b**) and bis-chelated silver (**10b**) complex in moderate and good yields (51% and 91%, respectively).

Complimentary to the one step preparation of the bis-chelated complexes, **10a-b** and **11**, a two step approach could be undertaken, incorporating the bridged analogues (**8a-b** and **9**) as intermediates. (Scheme 1, step F).

The corresponding gold and silver complexes (Scheme 1) were fully characterised by multinuclear NMR spectroscopy, elemental analysis (except **8b** and **9**) and mass spectrometry. The ^1H NMR spectra of the complex **8a**, **9**, **8b**, **10a**, **10b** and **11** showed a deshielding of the ethylenic protons on complexation compared to that of the free ligand. The deshielding of the ethylenic protons has been observed for various other complexes in the literature, such as $[(\text{AuCl})_2(\text{dnpype})]$, [28] where $n = 2 - 4$, and $\text{dnpype} = 1,2\text{-bis}(\text{di-}n\text{-pyridylphosphino})\text{ethane}$, $[\text{Au}(\text{dppe})_2]\text{Cl}$, [1,16] $[\text{Ag}(\text{dppe})_2]\text{NO}_3$, [30] $[\text{Ag}(\text{dnpype})_2]\text{NO}_3$, [31] and $[\text{Cu}(\text{dppe})_2]\text{BF}_4$, [32] Furthermore, the ethylenic protons of the bridged di-gold(I) complexes, **8a** and **9**, are more deshielded than those of the bis-chelated complexes **10a** and **11**. This is consistent with the reported bridged complex $[(\text{AuCl})_2(\text{dnpype})]$ vs the bis-chelated complex $[\text{Au}(\text{dnpype})_2]\text{Cl}$, [29]

The ^{31}P NMR spectra of the bridged di-gold(I) (**8a**) and bis-chelated gold(I) (**10a**) in deuterated chloroform showed signals around δ 32.4, 33.2 and 15.1, 15.5 ppm, respectively (Table 1). The observed trend in ^{31}P NMR spectra of **8a** and **10a**, where the chemical shift of **8a** is deshielded to a greater extent than that of **10a**, is consistent with that observed for the dppe analogues, $[(\text{AuCl})_2(\text{dppe})]$ and $[\text{Au}(\text{dppe})_2]\text{Cl}$, [1,16,17] The ^{31}P NMR spectrum in DMSO of **9** and **11** showed signals at δ 31.5 and 22.3, respectively. This is also consistent with the observations made for complexes $[(\text{AuCl})_2(\text{dppe})]$ and $[\text{Au}(\text{dppe})_2]\text{Cl}$. However, the reported $^{31}\text{P}\{^1\text{H}\}$ resonance of the analogous complex $[(\text{AuCl})_2(\text{dppey})]$, is at 12.8 ppm (Table 1). [1]

The $^{31}\text{P}\{^1\text{H}\}$ NMR spectra of the bridged complex **8b** and bis-chelated complex **10b** showed a doublet at δ 9.5 ppm [$J_{\text{Ag-P}} = 225$ Hz] and δ -2.1 ppm [$J_{\text{Ag-P}} = 240$ Hz], respectively.

A similar bridged silver complex $[(\text{Ag}_2\text{O}_4\text{C}_{12}\text{H}_6)(\text{dppe})]$ with a carboxylic group bridging two silver atoms, showed a coupling constant of $J_{\text{Ag-P}} = 230$ Hz in CDCl_3 , [18] A coupling constant for the bis-chelated complex $[\text{Ag}(\text{dppe})_2]\text{NO}_3$ with the value of $J_{\text{Ag-P}} = 231 / 266$ Hz had been reported. [30]

Due to the hygroscopic nature of the compounds accurate elemental analyses could not be performed. Degrees of deviation were overcome by accounting for the presence of co-crystallised solvent in the crystal lattice, which were not removed after extended periods under high vacuum. This has been previously observed with a similar series of compounds within our research group, [33] where structures were confirmed by x-ray diffraction.

Conclusions

This paper reports the successful preparation of two alkyl, aryl-substituted bis-phosphines ligands, differing only in the composition of their backbone, and their subsequent complexation with gold and silver.

Two synthetic approaches were investigated in order to obtain the desired ligands. The first method involved the synthesis of butyldiphenylphosphine from triphenylphosphine (**7**), and thereafter the desired ligand was obtained via a lithium butylphenylphosphide intermediate. The second method involved the synthesis directly from bis-phosphines, dppe (**1**) and dppey (**2**).

The synthesis of two-coordinate (bridged) and four coordinate (bis-chelate) novel gold(I) complexes **8a**, **9** and **10a**, **11**, and silver (I) complexes **8b** and **10b** has been achieved. All of the synthesised complexes compared favourably to analogues reported in literature.

Acknowledgements

The authors would like to thank Project AuTEK (Mintek and Harmony Gold) for permission to publish this paper and for financial support. Further thanks go to University of the Witwatersrand for use of their facilities.

About the Authors



Mr. David Khanye

David Khanye is currently a first year PhD student at the University of Cape Town working on gold complexation of thiosemicarbazones and isothiazoles under supervision of Prof. Kelly Chibale, Dr. Judy Caddy and Dr. Greg Smith.



Dr. Marcus Layh

Dr. Marcus Layh is currently a research associate at the University of Münster and has held previous industrial and academic positions in Germany, the UK and South Africa. His research interests are in the field of main group organometallic chemistry.



Dr. Judy Caddy

Judy joined Mintek in 2003 after obtaining her PhD in Organic Chemistry at the University of Johannesburg (Rand Afrikaans University). She began her research career looking at the synthesis and biological activity of a variety of phosphine compounds in a secondment to University of Witwatersrand. During this time Judy undertook a research visit to Heidelberg, Germany, where she investigated the gold labelling of neurologically active pentapeptides. Shortly after her return to South Africa she began heading up the AuTEK Biomedical Programme, along with taking on an honorary position at the University of Witwatersrand. Over the past three years Judy has actively supervised and co-supervised student projects at collaborating universities, along with her research activities at Mintek, where she is now involved in the development of therapies for cancer, HIV and malaria.

References

- 1 S.J. Berners-Price, P.J. Sadler, *Inorg. Chem.*, 1986, **25**, 3822 – 3827
- 2 B.R. Kimpton, W. McFarlane, A.S. Muir, P.G. Patel, J.L. Bookham, *Polyhedron*, 1993, **12**, 2525 – 2534
- 3 *Comprehensive Coordination Chemistry II*, Vol. 1, Editors, J.A. McCleverty, T.J. Meyer, 1st Ed. 2004, Pergamon, Elsevier, Ltd, London
- 4 T.S. Chou, Chung-Huang Tsao, Su Chun Hung, *J. Org. Chem.*, 1985, **50**, 4329 – 4332
- 5 A. Bollman, K. Blann, J.T. Dixon, F.M. Hess, E. Killian, H. Maumela, D.S. McGuinness, D.H. Morgan, A. Neveling, S. Otto, M. Overett, A.M.Z. Slawin, P. Wasserscheid, S. Kuhlmann, *J. Am. Chem. Soc.*, 2004, **126**, 14712 – 14713
- 6 J.S. Lewis, S.L. Heath, A.K. Powell, J. Zweit, P.J. Blower, *J. Chem. Soc., Dalton. Trans.*, 1997, 855 – 861
- 7 R.H. Crabtree, *J. Organomet. Chem.*, 2005, **690**, 5451–5457
- 8 M.J. McKeage, S.J. Berners-Price, P. Galettis, R.J. Bowen, W. Bouwer, L. Ding, L. Zhuang, B.C. Baguley, *Cancer Chemother. Pharmacol.*, 2000, **46**, 343 – 350
- 9 P. Le Floch, *Coord. Chem. Rev.*, 2006, **250**, 627–681
- 10 M.S. Balakrishna, R.M. Abhyankar, J.T. Mague, *J. Chem. Soc., Dalton Trans.*, 1999, 1407–1412
- 11 N. Mézailles, L. Ricard, F. Mathey, P. Le Floch, *Eur. J. Inorg. Chem.*, 1999, 2233–2241
- 12 G.A. Bowmaker, J.P. Williams, *Aust. J. Chem.*, 1994, **47**, 451–460
- 13 S.J. Berners-Price, R.J. Bowen, P. Galettis, P.C. Healy, M.J. McKeage, *Coord. Chem. Rev.*, 1999, **185 – 186**, 823–836
- 14 R.J. Bowen, A. C. Garner, S.J. Berners-Price, I.D. Jenkins, R.E. Sue, *J. Organomet. Chem.*, 1998, **554**, 181–184
- 15 F. Mainza, F. Spindler, M. Thommen, B. Pugin, C. Malan, A. Mezzetti, *J. Org. Chem.*, 2002, **67**, 5239 – 5249
- 16 S.J. Berners-Price, R.J. Bowen, M.A. Fernandes, M. Layh, W.J. Lesueur, S. Mahepal, M.M. Mtotywa, R.E. Sue, C.E.J. van Rensburg, *Inorg. Chim. Acta*, 2005, **358**, 4237 – 4246
- 17 S.J. Berners-Price, M.A. Mazid, P.J. Sadler, *J. Chem. Soc., Dalton Trans.*, 1984, 969 – 974
- 18 A.F.M.J. van der Ploeg, G. van Koten, A.L. Spek, *Inorg. Chem.*, 1979, **18**, 1052 – 1060.
- 19 A.F.M.J. van der Ploeg, G. van Koten, *Inorg. Chim. Acta*, 1981, **51**, 225–239
- 20 R.J. Bowen, J. Caddy, M.A. Fernandes, M. Layh, M. Mamo, R. Meijboom, *J. Organomet. Chem.*, 2006, **691**, 717–725
- 21 R.J. Bowen, M.A. Fernandes, P.W. Gitari, M. Layh, R.M. Moutloali, *Eur. J. Inorg. Chem.*, 2005, 1955–1963
- 22 R.J. Bowen, D. Camp, Effendy, P.C. Healy, B.W. Skelton, A.H. White, *Aust. J. Chem.*, 1994, **47**, 693 – 701
- 23 N.K. Roberts, S.B. Wild, *J. Am. Chem. Soc.*, 1979, 101, 6254–6260
- 24 J. Dogan, J.B. Schulte, G.F. Swiegers, S.B. Wild, *J. Org. Chem.*, 2000, **65**, 951– 957
- 25 R.S. Dickson, P. S. Elmes, W.R. Jackson, *Organometallics*, 1999, **18**, 2912–2914
- 26 A.L. Airey, G.F. Swieger, A.C. Willis, S.B. Wild, *Inorg. Chem.*, 1997, **36**, 1588–1597
- 27 P. Brooks, M.J. Gallagher, A. Sarroff, *Aust. J. Chem.*, 1987, **40**, 1341–1351
- 28 A.M. Aguiar, D. Daigle, *J. Am. Chem. Soc.*, 1964, **86**, 2299 – 2300
- 29 S.J. Berners-Price, R.J. Bowen, T.W. Hambley, P.C. Healy, *J. Chem. Soc., Dalton Trans.*, 1999, 1337–1346
- 30 S.J. Berners-Price, C. Brevard, A. Pagelot, P.J. Sadler, *Inorg. Chem.*, 1985, **24**, 4278–4281
- 31 S.J. Berners-Price, R.J. Bowen, P.J. Harvey, P.C. Healy, G.A. Koutsantonis, *J. Chem. Soc., Dalton Trans.*, 1998, 1743–1750
- 32 P. Comba, C. Katsichtis, B. Nuber, H. Pritzkow, *Eur. J. Inorg. Chem.*, 1999, 777–783
- 33 F.H. Kriel “Gold(II) Phosphine Complexes as Selective Anti-Tumour Agents: Studies centred around the use of a dialkyl-hydrazine backbone”, PhD Thesis, University of Witwatersrand, School of Chemistry, to be submitted January 2007